



The influence of raw material on fracture attributes used in projectile analysis: First results from a bench test experiment[☆]

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ABSTRACT

Fracture attributes are commonly used in lithic technological and functional analysis, but the influence of raw material on fracture morphologies has rarely been formally investigated. This study presents a bench test experiment designed to evaluate the influence of raw material on fracture development under similar stress conditions. Specimens made of flint, quartzite, quartz, glass, dolerite and obsidian were tested. The results show clear relationships between raw material and several fracture attributes, particularly fracture terminations, the occurrence of fissured terminations and the length of fracture propagation. These results contribute to a better understanding of the mechanisms underlying observed fracture variability and place into perspective the interpretative value of various fracture attributes in functional analysis, particularly in projectile identification.

1. Introduction

Non-flint raw materials constitute a vast part of the archaeological record, yet they remain comparatively under-represented in the experimental and methodological foundations that underpin lithic functional analysis. Many of these rocks are multi-mineral aggregates with variable crystalline structures and consequently varied in their homogeneity. These differences condition how the material responds to stress and initiates and propagates cracks. Consequently, fracture characteristics should not be assumed to be raw material-neutral.

This issue is particularly important for projectile studies, which rely heavily on the identification and interpretation of fracture patterns produced during impact. Historically, experimental programmes that have shaped the analytical framework for projectile analysis have been developed primarily on flint (Barton and Bergman, 1982; Fischer et al., 1984; Frison, 1989; Moss and Newcomer, 1982; Odell, 1978; O'Farrell, 1996; Plisson and Beyries, 1998). More recently, important efforts have extended experimental work to other raw materials, including quartz (Pargeter et al., 2016; Taipale and Rots, 2019), quartzite (Lazuén, 2012; Lombard et al., 2004; Schoville and Brown, 2010), obsidian (Hutchings, 2011, 1997; Lafayette and Smith, 2012) and banded iron stone (Wilkins et al., 2012) amongst others. These studies have produced dedicated reference collections for several sites. However, at a more general level,

our understanding remains limited of the extent to which raw material variability alone conditions the development and frequency of fracture attributes commonly used to interpret projectile use. To begin to address this, we designed a bench test experiment in which we applied similar stress to experimental lithic points made from six different raw materials to detect potential raw-material induced variation in the resulting fractures and their attributes.

2. Methods

2.1. Raw material and experimental protocol

To test the potential differences between raw materials, we designed an experimental protocol aimed at subjecting knapped lithic artefacts to controlled stress conditions and observing breakage phenomena. Sixty-six pieces were knapped from six different raw materials, flint, quartzite, xenomorphic (vein) quartz, dolerite, obsidian and glass, resulting in a sample of 12 pieces per raw material. The flint derives from the Harmignies quarry near the city of Mons in Belgium. The quartzite was collected in a riverbed close to the archaeological site of Umbeli Belli Rock Shelter, situated near Scottburgh, KwaZulu-Natal, in South Africa. The dolerite was collected in the riverbed of the uTongathi river close to Sibhudu Cave located north of Durban in KwaZulu-Natal, South Africa.

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The quartz was collected in Sipoo, southern Finland. The obsidian was collected during surveys in Ethiopia and the glass was sourced from an industrially produced thick plate.

Obsidian, like glass, is an amorphous, noncrystalline raw material with a silica content generally around $\sim 70\text{--}78\%$. When it is at its most homogeneous, it presents a highly predictable fracture, although inclusions of varying sizes and shapes, as well as rare but significant residual thermal stresses, can interfere with its fracture qualities (Tsirk, 2014). Flint is a cryptocrystalline rock consisting predominantly of silica (Tsirk, 2014). The Harmignies flint we used in the experiment is generally of high knapping quality. It can contain coarser-grained (microcrystalline) inclusions, but these are small-sized and infrequent in the samples included here, and the flint test pieces can be considered homogeneous in their raw material properties.

Xenomorphic quartz, commonly termed vein quartz, is a polycrystalline aggregate (Mourre, 1996; Rodríguez-Rellán, 2016). Its fracture toughness is higher than that of automorphic (single-crystal) quartz because it lacks continuous cleavage planes (Schultz et al., 1994), but it presents abundant flaws, which can lead to the creation of multiple secondary fracture fronts and to overall unpredictable fracture propagation (Cotterell and Kamminga, 1990). Exaggerated fracture dimensions have been documented when fracture paths encounter zones of structural weakness (Taipale and Rots, 2019).

'Quartzite' is a term variably applied to quartz-rich sandstones transformed through silica cementation and/or metamorphism. Their field classification remains a challenge (Howard, 2005; Pedergrana et al., 2017; Pedergrana et al. 2018; Prieto et al., 2026 (this volume); Skolnick, 1965). Quartzites present variable fracture qualities depending on, for instance, their grain size and petrogenesis, but they are generally tough rocks due to the interlocked texture of their constituent grains (Skolnick, 1965; Tsirk, 2014). In the absence of petrographic data, we do not attempt to assign the variety included in the experiment to a particular petrogenetic group but can note that the raw material is compact and presents transgranular fracture.

Dolerite is an igneous rock. Analyses of samples from the Sibhudu dyke and the uThonghati River have demonstrated a silica content around 51–52%, with Al_2O_3 (aluminium oxide), Fe_2O_3 (iron oxide), MgO (magnesium oxide) and CaO (calcium oxide) among the other main constituents. Mechanical tests could characterise the coarser varieties that at least superficially correspond to the one tested here as tough, rigid, and presenting rough fracture surfaces (Wadley and Kempson, 2011).

To approximate breakage during projectile impact, we opted for

using knapped lithics of similar morphologies. This setup has the disadvantage of introducing additional, morphological variables into fracture formation, as opposed to the use of machine-cut specimens that would allow closer replication of shape. However, the use of knapped lithics has the benefit of producing results that are more directly comparable to archaeological impact fractures and thus informative of the challenges related to raw material variability in real-life analytical settings.

We chose the backed triangular piece as a target morphology to facilitate producing comparable shapes and sizes across the different raw materials (Fig. 1). Backing thin blanks is a technique that allows a high degree of control over morphology while being less sensitive to differences in the ability of raw materials to propagate retouch removals. Quartzite, quartz, and dolerite pieces showed greater variability due to their knapping qualities.

As fracture attributes currently play a key role in archaeological projectile analysis, we decided to focus our protocol on approximating impact stress conditions. Projectile impact is mainly compressive but involves a variable bending component, the magnitude of which depends on the weapon delivery system (Coppe et al., 2022). We chose to approximate the stress generated on impact by a throwing spear. It can be produced by applying a stress to the sample at an angle of 10° from the axis of the point (Coppe et al., 2022).

To achieve this specific angle and consequently the desired combination of compressive and bending stresses in a reproducible manner, we used a universal testing machine Shimadzu Autograph AG-S-X (maximum 10 kN). We fixed the lithic piece in a clamp (Fig. 2.a,b) and the test bench was set to apply a vertical force with a flat-tipped bone indenter (Fig. 2.c) on the sample at a fixed speed of 5 mm/min until breakage. The stress was applied on the dorsal surface of the sample to create a fracture that propagated onto the ventral surface. This choice was made to avoid the influence of dorsal ridges on fracture propagation. We also chose not to introduce weaknesses into the specimens artificially so as to avoid their influence on fracture propagation and the resulting fracture morphologies. This decision was made to better approximate realistic projectile impact conditions. However, the absence of pre-existing weaknesses can result in greater variability in both the force required to initiate fracture and the location of fracture initiation. To closely observe the breakage phenomenon, we recorded three tests per raw material with a Photron Nova S12 camera at 30 000 frames per second with a resolution of 1024 on 512 pixels. The force required to initiate a break was recorded for all test pieces.



Fig. 1. Example of experimental pieces produced in obsidian, dolerite, quartzite, quartz, flint, and industrial glass.



Fig. 2. Experimental setup for bench testing. (a) Overview of the test bench, light disposition and filming system, (b) view of the position of the piece before stress application, showing the grip and the angle variation system, and (c) close-up of the contact between the bone compressor and a glass specimen prior the stress application.

2.2. Analytical protocol

All the fractures were observed with a stereomicroscope Zeiss V 12 (magnifications 8–100 ×) under oblique lighting and imaged with a Zeiss V16 macroscope and AxioVision software and Helicon Focus for z-stacking. Two randomly selected dolerite specimens were additionally examined and imaged with the help of JEOL IT300 scanning electron microscope (SEM) at magnifications between 30 and 200 × in secondary electron mode at 20 kV and 40 Pa.

All the fractures were described precisely with an attribute-based system (Coppe and Rots, 2025), with the goal of understanding potential raw material-induced variation in fracture attributes. The effect of inter-sample size and shape variability was examined by measuring the width and thickness of the fracture surfaces of the machine-induced breaks.

We performed multivariate statistical analysis to assess which experimental covariates – raw material, blank dimensions and break cross-section surface area – explain the morphology of fractures observed on the tools, and to what extent. We used two complementary formulations of permutation-based multivariate analysis of variance (PERMANOVA; 999 permutations; Anderson 2001) on a distance matrix adapted to a dataset with mixed – binary, ordinal and numeric – data (Gower 1971; Podani 1999). Alongside, we used the multivariate Levene test (betadisper; Anderson 2006; Anderson & Walsh 2013) to assess the validity of the previous results. The complete methodology, plots and results can be found in the [Supplementary Material](#) (Supplementary Text 2).

To go further and detect potential raw material-induced variation in specific fracture attributes, we analysed differences in the frequency of key fracture attributes across raw materials. First, the relative frequencies of bending breaks and associated secondary damage (SD) were analysed to assess whether certain raw materials exhibit a greater propensity to develop secondary damage, a fracture category widely considered relevant for identifying projectile elements (Coppe and Rots, 2025; Dockall, 1997; Fischer et al., 1984).

Second, termination morphologies were examined. Certain terminations have been regularly considered to have diagnostic value in use-wear studies. For example, step terminations associated with bending breaks have relevance for projectile identification (Fischer et al., 1984; For discussion see Rots and Plisson, 2014; Coppe and Rots, 2017, 2025) and have been reported to correlate with hard worked materials in the broader field of use-wear analysis (Odell, 1981; Tringham et al., 1974). Third, the frequency of fissured terminations, a criterion also used in

projectile identification (Coppe and Rots, 2025), was analysed to evaluate the extent to which it varies. Finally, the propagation length of the fracture was examined. This attribute is also regularly used in projectile analysis, particularly in efforts to link lithic damage patterns to different weapon delivery systems (Clarkson, 2016; Iovita et al., 2016, 2014; Sano, 2016; Sano et al., 2019; Sano and Oba, 2015, 2014; Coppe et al., 2019).

The results were statistically analysed with the help of Jamovi (version 2.6.44). Associations between qualitative variables were assessed using Fisher's exact test. This test was selected because the expected frequencies in several cells were low (below five). This test evaluates deviations between observed and expected frequencies. The expected frequencies correspond to the distribution that would be expected if no relationship existed between the variables under investigation. To explore the contribution of individual cells to the overall χ^2 statistic, adjusted residuals were examined. These residuals express the difference between observed and expected frequencies relative to their theoretical standard deviation; values below -2 indicate significant under-representation, whereas values above $+2$ indicate significant over-representation. Associations between qualitative and quantitative variables were assessed using the Kruskal–Wallis test. This non-parametric test was selected because the data did not satisfy the assumptions of normality or homogeneity of variances. When a significant overall effect was detected, differences between raw materials were further explored using pairwise comparisons with the Dwass–Steel–Critchlow–Fligner test. This approach enabled the identification of specific pairs exhibiting significant differences in the quantitative variables under investigation.

3. Results

3.1. General remarks

The choice to avoid introducing predefined weaknesses into our specimens prior to breakage led to high variability in the force required for crack initiation (Fig. 3). Despite this variability, glass, quartz, flint and obsidian display broadly overlapping ranges with similar median values. Quartzite clearly contrasts by requiring higher forces to initiate a crack (Fig. 3), which is consistent with the comparably high resistance of the material to fracture initiation reported previously (Cotterell and Kamminga, 1987).

Despite the attempt to produce lithics with comparable dimensions and morphology, a degree of variation was introduced to the test sample

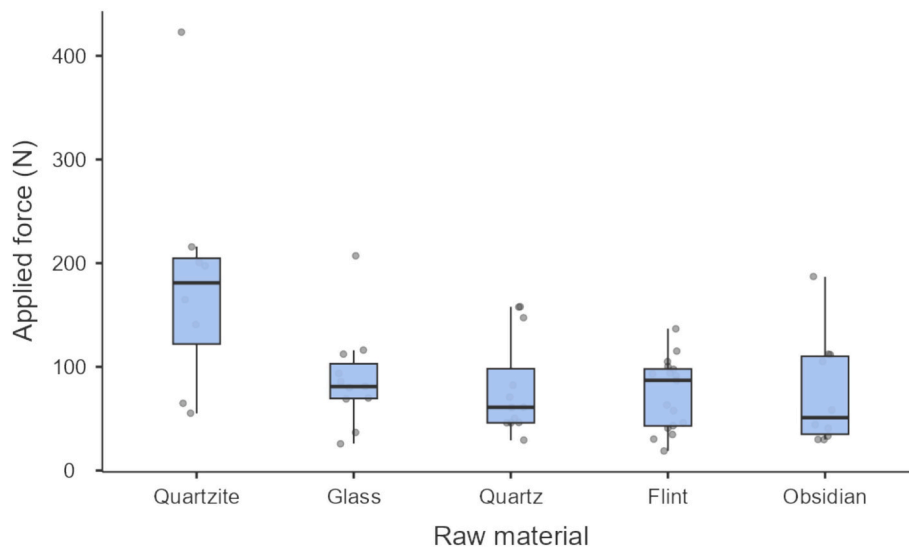


Fig. 3. Force (Newton) required to initiate a fracture in the test sample (N. 75).

by the knapping properties of the raw materials. The flint, glass, and obsidian pieces are closely similar, but the quartzite, quartz, and dolerite pieces show greater size and shape variability. However, break cross-sections showed similar variability across raw materials with the exception of flint, which exhibits lower mean values and a more restricted distribution for both width and thickness (Figs. 4 and 5).

During preliminary analysis, it rapidly became apparent that for dolerite, fracture paths could not be reliably identified using stereomicroscopy alone. SEM imaging of two dolerite pieces, selected randomly among the specimens that posed a challenge to the stereomicroscopic characterisation, demonstrated that fracture initiations on this variety are irregular and terminations can be hard to detect and/or characterise. This derives from the tendency of the rock to fracture both across and around the large crystals incorporated in the matrix, which also contributes to rough, irregular fracture surfaces (Fig. 6). The impact of large crystals on fracture expression corresponds well with the previous characterisation of Sibhudu dolerite that could correlate large grain size and rough fracture surfaces (Wadley and Kempson 2011). These qualities pose serious challenges for describing the initiations and

terminations of the fractures using the flint-based attribute system we opted for. To mitigate the effects of lacking or unreliable data for this raw material, we excluded it from the statistical comparisons, focusing on the five other raw materials.

This divergent behaviour of dolerite is also clearly observable in the video recordings. Apart from dolerite (SV1), propagation of the fracture front can be visually tracked for all raw materials, although fractures propagate at markedly lower velocities in flint (SV2) and in quartzite (SV3) than in glass (SV4), obsidian (SV5) and quartz (SV6). These apparent differences in fracture propagation speed represent an aspect that warrants further investigation in future research. The apparent change in the orientation of the bone indenter between SV1 and SV2 is due to a slight difference in camera angle between recording sessions conducted on separate days, rather than any modification of the experimental setup.

3.2. General multivariate statistical analysis

Permutation-based multivariate analysis of variance (PERMANOVA)

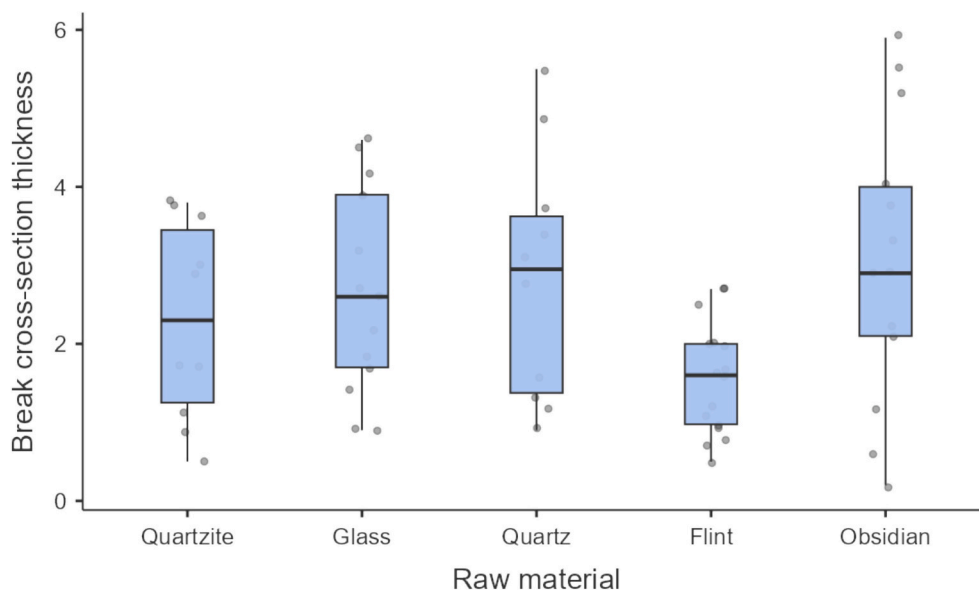


Fig. 4. Thickness of the cross-section (mm) of bending breaks by raw material (N:65).

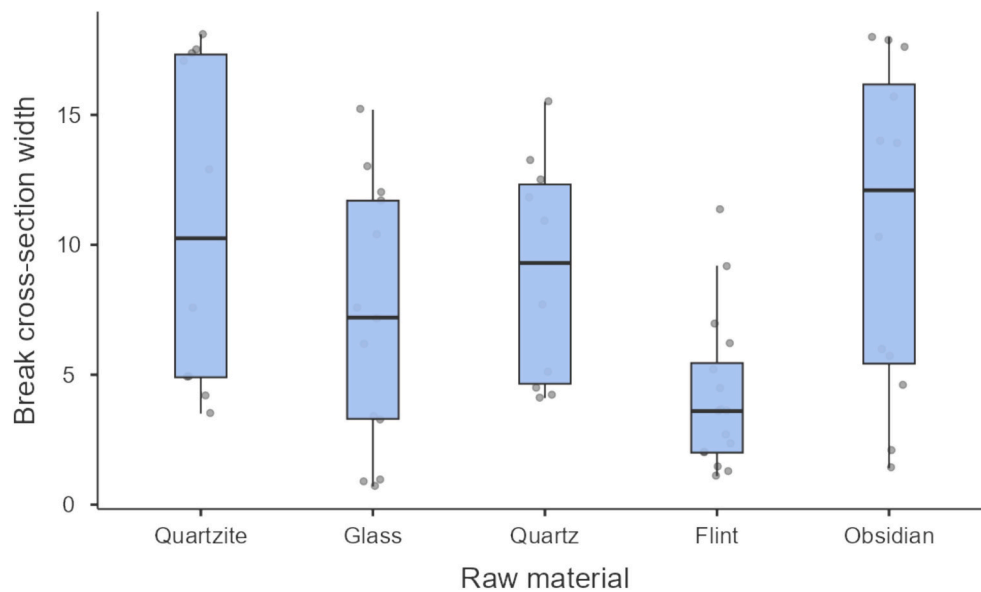


Fig. 5. Width of the cross-section (mm) of bending breaks by raw material (N:65).

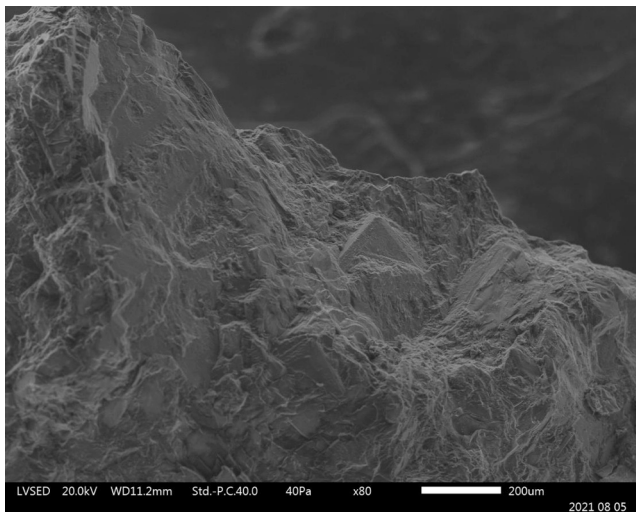


Fig. 6. SEM image of the area of break initiation on a dolerite test piece (Exp82/140), showing the propagation of the crack through and around crystals and matrix (80x) (photo Dries Cnuts).

applied to Gower distances over 90 fractures on 60 tools (excluding the dolerite and one fracture 117_32_01 for incomplete data) identified raw material as the primary determinant of fracture morphology, independently accounting for 11.6% of total variance ($R^2_{\text{marginal}} = 0.116$, $p = 0.001$). Break cross-section area was the only other significant predictor ($R^2_{\text{marginal}} = 0.044$, $p = 0.003$). All the remaining covariates, blank dimensions and the shape of blank cross-section showed no significant independent effects (all $p > 0.05$). The sequential PERMANOVA shows similar results; however raw material explains a higher percentage of total variance ($R^2_{\text{sequential}} = 0.194$, $p = 0.001$). It absorbs the variance of other covariates (blank dimensions and the shape of blank cross-section) and illustrates confounding: in this dataset, blank dimensions and shape are not statistically independent from raw material (Table 5 in Supplementary Text 2).

The multivariate Levene tests revealed heterogeneous multivariate dispersion for raw material ($p = 0.001$), with quartz showing the highest mean distance to group centroid (0.178) and flint the lowest (0.080). The break cross-section classes were also heterogeneously dispersed (p

$= 0.002$): fractures in the lowest class (C11, $n = 56$) exhibited the greatest morphological variability (mean distance = 0.157), while those in the highest class (C14, $n = 4$) showed the least (0.078) (Table 4 in Supplementary Text 2). Full statistical results and outputs are provided in the Supplementary Text 2.

3.3. General fracture categories

After excluding the dolerite, 91 fractures were available for analysis. Two fractures lacked identifiable initiation features (Exp117_27_01; Exp117_27_02), preventing their classification as bending break (BB) or secondary damage (SD), and were therefore excluded from the analysis. The analysis was then conducted on 89 fractures.

The most frequent general fracture category is the bending break (BB; Fig. S1, Fig.S2) with 72 %, followed by secondary damage (SD; Fig. S3, Fig.S4, Fig.S5) at 28 %. The relative frequency of the general fracture categories (BB vs SD) does not differ significantly between raw materials (Fisher's exact test $p = 0.341$), but SD is slightly overrepresented in glass and quartz and slightly underrepresented in flint and obsidian (Table 1).

3.4. Termination morphology

A total of 91 terminations were analysed. The most represented termination is step with 40% (Fig.S1, Fig.S2), followed by hinge at 22% (Fig.S3), feather at 19%, complex at 10 %, snap at 8 % and non-attributed (N/A) at 2%. The distribution of termination morphologies varies significantly according to raw material (Fisher's exact test $p < 0.001$). These results indicate a dependency of termination morphology on raw material properties. The contingency table demonstrates these relationships (Table 2.). Feather terminations appear overrepresented in obsidian and less frequent than expected in flint and quartz. Step terminations are more frequent in flint and quartzite and less frequent in glass and obsidian. Hinge terminations are frequent in glass and underrepresented in quartzite and quartz. Complex terminations are uncommon but largely associated with quartz. Analysis of the adjusted residual shows that only the underrepresentation of hinges in quartzite and the overrepresentation of complex terminations in quartz and feather terminations in obsidian are significant (Table 3).

3.5. Occurrence of fissured terminations

The presence of fissures (Fig.S1, Fig.S2, Fig.S5) is also significantly

Table 1

Contingency table resulting from the Fisher's exact test depicting the observed and expected frequencies of bending breaks (BB) and secondary damage (SD) by raw material. Higher than expected frequencies are highlighted in bold and lower than expected frequencies in italics.

<i>Raw material</i>							
<i>General attribute category</i>		Quartzite	Glass	Quartz	Flint	Obsidian	Total
BB	Observed	10	13	12	16	13	64
	Expected	9.3	15.1	14.4	13.7	11.5	64
	% by column	76.9 %	61.9 %	60.0 %	84.2 %	81.3 %	71.9 %
SD	Observed	3	8	8	3	3	25
	Expected	3.65	5.9	5.6	5.3	4.5	25.0
	% by column	23.1 %	38.1 %	40.0 %	15.8 %	18.8 %	28.1 %
Total	Observed	13	21	20	19	16	89
	Expected	13	21	20	19	16	89.0
	% by column	100 %	100%	100%	100%	100%	100%

Table 2

Contingency table resulting from the Fisher's exact test depicting the observed and expected frequencies of different terminations by raw material. Higher than expected frequencies are highlighted in bold and lower than expected frequencies in italics.

<i>Raw material</i>							
<i>Termination</i>		Quartzite	glass	Quartz	Flint	Obsidian	Total
Feather	Observed	3	3	1	2	8	17
	Expected	2.4	3.9	3.8	3.5	3.4	17.00
	% by column	23.1 %	14.3 %	5.0 %	10.5 %	44.4 %	18.7 %
Step	Observed	7	6	8	11	4	36
	Expected	5.1	8.3	7.9	7.5	7.2	36.00
	% by column	53.8 %	28.6 %	40.0 %	57.9 %	22.2 %	39.6 %
Complex	Observed	1	2	6	0	0	9
	Expected	1.3	2.1	1.9	1.9	1.8	9.00
	% by column	7.7 %	9.5 %	30.0 %	0.0 %	0.0 %	9.9 %
Hinge	Observed	0	9	2	4	5	20
	Expected	2.9	4.6	4.4	4.2	3.9	20.00
	% by column	0.0 %	42.9 %	10.0 %	21.1 %	27.8 %	22.0 %
Snap	Observed	2	1	1	2	1	7
	Expected	1	1.6	1.5	1.5	1.4	7.00
	% by column	15.4 %	4.8 %	5.0 %	10.5 %	5.6 %	7.7 %
N/A	Observed	0	0	2	0	0	2
	Expected	0.3	0.5	0.4	0.4	0.4	2.00
	% by column	0.0 %	0.0 %	10.0 %	0.0 %	0.0 %	2.2 %
Total	Observed	13	21	20	19	18	91
	Expected	13	21	20	19	18	91
	% by column	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %

Table 3

Adjusted residuals of the Fischer's exact test for the association between termination and raw material. Values correspond to adjusted residuals from the contingency table analysis (Table 2). Positive values indicate the overrepresentation of a given termination type within a raw material, whereas negative values indicate underrepresentation. Absolute values higher than 2 (in bold) or lower than -2 (in italics) highlight the significant contributors to the Fischer's test.

<i>Termination simplified</i>	<i>Raw material</i>				
	Quartzite	Glass	Quartz	Flint	Obsidian
Feather	0.354	-0.4864	-16.841	-0.8968	2.143
Step	0.776	-0.8428	0.0312	11.876	-1.276
Complex	-0.262	-0.0537	2.961	-19.386	-1.887
Snap	0.879	-0.5212	-0.4641	0.4216	-0.344
Hinge	-2.390	18.032	-12.812	-0.0867	0.504
N/A	-0.756	-0.9608	17.145	-0.9139	-0.889

related to raw material (Fisher's exact test $p < 0.001$). The contingency table shows that the formation of fissured terminations is particularly recurrent in flint. In contrast, fissured terminations are completely absent in obsidian (Table 4). This relationship proved to be significant when the adjusted residuals were observed (Table 5). This phenomenon is connected to the type of termination: most of the fissures are associated with step terminations, even if some were recorded for hinge and complex terminations (Table 6).

3.6. Fracture propagation length

Fracture propagation length varies between raw materials. Quartzite is characterised by consistently shorter propagation phases, whereas flint shows higher values. Glass and obsidian exhibit generally intermediate values but are distinguished by the presence of pronounced outliers, indicating occasional development of longer propagations (Fig. 7). Under similar stress conditions, the propagation length differs significantly according to raw material (Kruskal-Wallis $\chi^2 = 13.9$, $df = 4$, $p = 0.008$, $\epsilon^2 = 0.156$). Pairwise comparisons reveal that this divergence is mainly due to the significant difference between quartzite and flint ($p = 0.038$). All other pairwise contrasts are non-significant, although comparisons between quartzite and obsidian approach the significance threshold ($p = 0.065$). The same can be observed between flint and quartz ($p = 0.07$) (Table 7).

4. Discussion

Across the multivariate analyses, raw material consistently emerges as the primary explanatory factor for fracture morphology, accounting for approximately 12% (Supplementary table 5) of total morphological variance in marginal permutation-based multivariate analysis of variance (PERMANOVA). This effect is robust to methodological variation, but must be considered alongside two sources of uncertainty: (i) heterogeneous within-group dispersion (Supplementary figure 1, 2; Supplementary Table 4), which may slightly inflate PERMANOVA

Table 4

Contingency table resulting from the Fisher's exact test depicting observed and expected frequencies of fissured termination by raw material. Higher than expected values are highlighted in bold and lower than expected values in italics.

		Raw material					Total
Fissure		Quartzite	Glass	Quartz	Flint	Obsidian	
No	Observed	9	17	16	7	18	67
	Expected	9.6	15.5	14.7	<i>14</i>	13.2	67.0
	% by column	69.2 %	81.0 %	80.0 %	36.8 %	100.0 %	73.6 %
Yes	Observed	4	4	4	12	<i>0</i>	24
	Expected	3.4	5.5	5.3	5	<i>4.8</i>	24.0
	% by column	30.8 %	19.0 %	20.0 %	63.2 %	<i>0.0 %</i>	26.4 %
Total	Observed	13	21	20	19	18	91
	Expected	13	21	20	19	18	91
	% by column	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %

Table 5

Adjusted residuals from the Fischer's exact test for the association between fissured termination and raw material. Values correspond to adjusted residuals from the contingency table analysis (Table 4). Positive values indicate the overrepresentation of fissured vs non-fissured terminations within a raw material, whereas negative values indicate underrepresentation. Absolute values higher than 2 (in bold) and lower than -2 (in italics) highlight the significant contributors to the Fischer's test.

Fissure	Raw material				
	Quartzite	Glass	Quartz	Flint	Obsidian
No	-0.187	0.385	0.328	<i>-2.07</i>	1.24
Yes	0.301	-0.688	-0.580	2.64	<i>-3.08</i>

Table 6

Frequency of fissured terminations by termination type and raw material.

Termination	Fissure		Total
	No	Yes	
Feather	17	0	17
	100.0%	0.0%	100.0%
Step	18	18	36
	50.0%	50.0%	100.0%
Complex	8	1	9
	88.9%	11.1%	100.0%
Snap	7	0	7
	100.0%	0.0%	100.0%
Hinge	16	4	20
	80.0%	20.0%	100.0%
N/A	1	1	2
	50.0%	50.0%	100.0%
Total	67	24	91
	73.6%	26.4%	100.0%

significance; and (ii) confounding between blank dimensions and raw material, which prevents unambiguous attribution of dimensional effects (Supplementary Table 5). The comparatively higher within-group dispersion observed in the quartz data suggests that this raw material exhibits more variable mechanical properties and fracture attributes than the other materials in the assemblage. This variability is consistent with the uneven resistance of the material to stress, deriving from its structural complexity (see [de Lombera Hermida, 2009](#)), and with earlier projectile experiments that documented considerable variation in impact fracture dimensions and crack propagation trajectories ([Taipale and Rots, 2019](#)).

Break cross-section is the only other covariate with a consistent, independent effect. Multivariate Levene tests reveal significant heterogeneity in dispersion across cross-section categories, suggesting that smaller cross-sections are associated with greater variability in fracture attributes.

None of the blank dimensions show a significant effect on the fracture attributes.

Overall, the other results indicate a clear relationship between raw

material and some of the examined fracture attributes. Several statistically significant relationships emerged, particularly concerning the occurrence of fracture terminations, even though all specimens were subjected to a similar mechanical stress. Additional tendencies were documented that deserve further investigation.

Quartzite and flint show a marked tendency towards the formation of step terminations, while hinge terminations are entirely absent in quartzite. In contrast, hinge terminations are favoured in glass and obsidian. Complex terminations are significantly overrepresented in quartz, whereas feather terminations occur predominantly in obsidian. The emergence of such marked differences is noteworthy, suggesting that intrinsic material properties play a major role in fracture development.

The formation of hinge terminations has long been associated with an excess of outward-directed force during fracture propagation. [Crabtree \(1968\)](#) described hinge terminations as resulting from excessive outward pressure, an interpretation later supported experimentally by [Cotterell et al. \(1985\)](#). Under these conditions, the fracture front deviates from a sub-parallel trajectory and propagates perpendicularly, until reaching the opposite surface with a curved termination profile ([Lawrence, 1979](#)). This outward force is not necessarily linked to the initial stress applied to the piece. The fractures at 10° incidence angle that we produced during the experiment typically initiated in bending and propagated into the material as a crack dominated by a compressive component (Mode II), but as the crack loses momentum, the stress fields may progressively become bending-dominated (Mode I) ([Tsirk, 2014](#)). [Cotterell and Kamminga \(1987\)](#) observed a substantial reduction in propagation velocity immediately prior to the formation of hinge terminations, supporting the initial interpretation by Crabtree ([Crabtree, 1968](#)).

Step terminations are associated with a distinct mechanical process. Following the definition proposed by [Crabtree \(1972\)](#), Cotterell and Kamminga described step terminations as fractures ending abruptly at a near right angle and distinguished between steps and steps associated with a fissure ([Fig. 7 in Cotterell and Kamminga, 1979, p. 105](#)). In both cases, step formation was interpreted as resulting from the initiation of a secondary fracture front, oriented perpendicular to the primary propagation direction, which abruptly interrupts the initial fracture ([Cotterell and Kamminga, 1979](#)). This phenomenon has been variously interpreted as resulting from the interaction of the fracture front with pre-existing flaws within the material ([Crabtree, 1968](#)), or from an increase in the bending component relative to the compressive component during propagation. Step terminations are frequently observed in thin removals ([Cotterell and Kamminga, 1979](#)).

These elements provide a coherent explanation for the results obtained in the present study. The overrepresentation of step terminations in flint and quartzite, combined with the absence of hinge terminations in quartzite, is likely linked to the lower tolerance of these materials to bending stresses ([Cotterell and Kamminga, 1987](#)). When the bending component becomes dominant during fracture propagation, these materials tend to fail abruptly rather than allowing a progressive

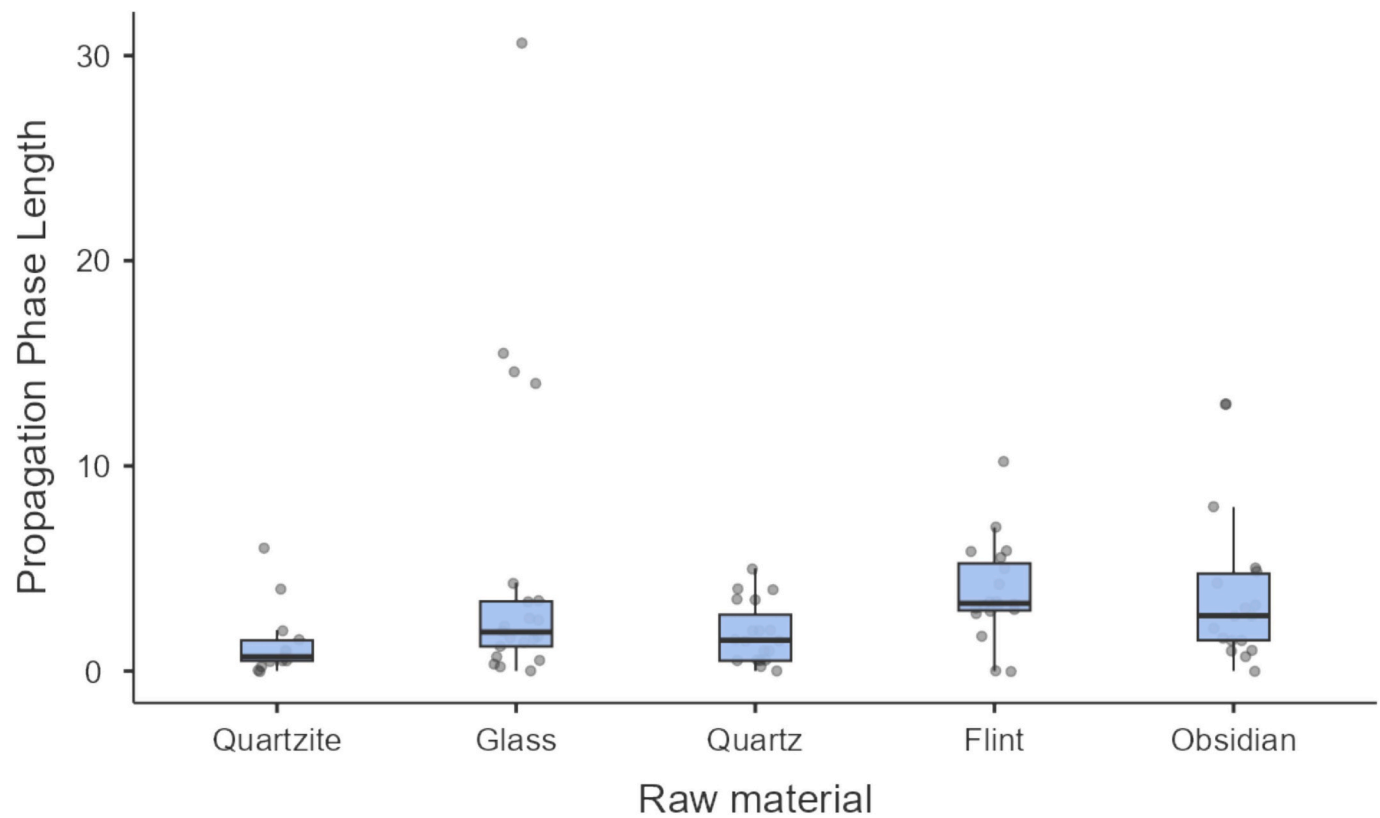


Fig. 7. Variation in propagation phase length (mm) by raw material (n = 89).

Table 7

Post hoc pairwise comparison of propagation phase length across raw materials following the Kruskal–Wallis ANOVA. The analysed sample is constituted of 90 fractures (quartzite n = 13, glass n = 21, quartz n = 19, flint n = 19, obsidian n = 18).

Raw material		W	P
Quartzite	Glass	2.911	0.239
Quartzite	Quartz	1.697	0.752
Quartzite	Flint	3.995	0.038
Quartzite	Obsidian	3.718	0.065
Glass	Quartz	−1.477	0.835
Glass	Flint	2.185	0.533
Glass	Obsidian	0.658	0.990
Quartz	Flint	3.680	0.070
Quartz	Obsidian	2.629	0.340
Flint	Obsidian	−1.677	0.760

redirection of the fracture front (SV2 flint, SV3 quartzite). Additional complications may be introduced by the structural properties of quartzite that make fracture attributes generally ill-defined (Ollé et al., 2016). Smooth, rounded terminations described as ‘hinges’ may simply be rare occurrences in these grainy rocks. In contrast, glass and obsidian are more homogeneous and resistant to elastic deformation (Cotterell and Kamminga, 1987). This allows the fracture front to change direction without a catastrophic arrest when the bending stress exceeds compressive stresses, favouring hinge termination (SV4 glass), or even feather termination when the fracture path is very close to the external surface (SV5, obsidian).

The occurrence of fissured terminations appears to derive from the same mechanics. Historically, fissures have been described almost exclusively in association with step terminations (Fig. 1 in Ho Ho Committee, 1979, p. 134). In our dataset, fissures are indeed most frequently associated with step terminations, but they also occur in

combination with hinge and complex terminations. High-speed video recordings show that the fissures develop prior to the formation of the final step termination (SV1). The compressive component initially drives fracture propagation until its available energy becomes insufficient to sustain further advance of the fracture front. At this point, the bending component takes over, causing the removal to fracture upstream of the final fracture front, and leaving a fissured fragment partially attached to the negative part of the fracture (Cotterell and Kamminga, 1979; Crabtree, 1968). The significant association observed between flint and fissured terminations is not surprising, given the strong tendency of this material to produce step terminations. Conversely, the absence of fissured terminations in obsidian is consistent with the low frequency of step terminations in this raw material. Once again, this may be explained by the lower resistance of flint to bending stresses compared to obsidian.

These results have important implications for projectile identification. Fissured terminations have recently been proposed as an important element in projectile identification on the basis of a reference framework consisting of flint (Coppe and Rots, 2025). The mechanical tests presented here indicate that raw material has an important influence on the occurrence of fissured terminations. We therefore emphasise that the absence of fissured terminations in non-flint raw materials (particularly obsidian) is not necessarily an argument against projectile use.

With regard to the length of fracture propagation, we observed that the more homogeneous raw materials in the sample (flint and obsidian) tend to permit longer fracture propagation phases compared to more heterogeneous materials, such as quartzite and quartz. Interruption of fracture paths in quartzite may relate to its relatively high fracture toughness, whereas cracks in quartz can rarely propagate long distances without encountering a flaw that causes some of the energy to dissipate into secondary fracturing. In some cases, however, such flaws may also lead to anomalously long fracture propagations (Taipale and Rots, 2019).

The results for glass are, however, unexpected. We recorded the

longest propagation phases for glass compared to other raw materials, but these values proved noticeable outliers. The median propagation length that we recorded for glass is lower than what was observed for flint and obsidian.

These findings emphasise that functional (but also technological) studies should rely on a reference framework based on (or including) artefacts made from raw materials that correspond or closely match raw materials present in the studied archaeological assemblage. Reference collections based on flint alone are unlikely to provide a sufficiently reliable reference for the wide range of raw materials encountered in archaeological contexts. Care should be taken to not directly transfer identification criteria between raw materials without prior experimental verification.

Mechanical testing provides a useful means for isolating the influence of individual variables on fracture morphology and, by extension, for improving our understanding of fracture formation processes. Such understanding is needed to support functional analysis of archaeological assemblages. A central difficulty inherent to this approach lies in the strong interdependence of the phenomena observed, which are often shaped by the combined effects of multiple parameters. Subjecting a large number of specimens to strictly identical mechanical constraints, while maintaining closely comparable morphologies across manually produced samples made from different raw materials, remains challenging. This difficulty was encountered during our experiment. While the morphology of flint, glass, and obsidian pieces were relatively homogeneous, achieving comparable control for quartz and quartzite (as well as dolerite) was considerably more difficult, and several specimens exhibited thicker and larger cross-sections. Nevertheless, fractures produced by the bench breakage test presented comparable ranges of thickness (Fig. 4) and width (Fig. 5) across the sample. This highlights the comparability of the fractures despite the issues encountered in artefact replication. The results obtained in this study are also influenced by the characteristics of the bench test that was used. Future research should also investigate the combined influence of loading velocity and raw material properties on fracture morphology and propagation. While the present experiment was conducted under loading conditions, projectile impacts involve substantially higher strain rates, which may interact differently with the mechanical properties and internal structure of each raw material. Exploring this cross-influence would provide an important step towards a more comprehensive understanding of fracture formation processes in archaeological lithic assemblages. For these different reasons, the results presented here must be regarded as preliminary. However, the identification of several significant associations between particular fracture attributes and raw materials highlights the value of the present experimental approach. Moreover, the numerous tendencies observed are encouraging and likely to reach greater statistical robustness with an extended sample size.

5. Conclusion

Our study highlights the influence of raw material properties on fracture formation. The multivariate analysis consistently identifies raw material as the primary source of variance, followed by break cross-section area, although both effects remain modest in magnitude and should be interpreted cautiously given the methodological uncertainties outlined above. Future experimental designs will need to implement stricter control over blank dimensions in order to disentangle their contribution from that of raw material. The preliminary trends identified here for raw material and break cross-section area will require confirmation through larger and more systematically controlled samples.

Moreover, further specific statistical tests show that, under controlled conditions, marked differences emerged in fracture terminations, occurrence of fissured terminations, and propagation length, demonstrating that fracture morphologies cannot be interpreted without considering the effect of raw material properties. In particular,

differences in tolerance to bending stresses appear to be an important factor. These results reinforce the need to invest in reference collections produced in closely comparable raw materials for each archaeological context. Moreover, caution is required when using specific fracture attributes or propagation length measurements as interpretative criteria if the reference framework from which these criteria are derived was not established using the same raw materials as those present in the archaeological assemblage under study. While our present results remain preliminary, they document the potential of controlled mechanical experiments to refine our understanding of fracture processes in lithic functional and technological research. Expanding the experimental sample and achieving stricter morphological control across different raw materials will be essential steps towards the development of more robust protocols which will ultimately improve our understanding of how tools made from different raw materials break and how the mechanical stresses associated with their use are variably reflected in their fracture attributes.

CRediT authorship contribution statement

Justin Coppe: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Noora Taipale:** Writing – review & editing, Visualization, Formal analysis, Data curation, Conceptualization. **Solène Escarguel:** Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Veerle Rots:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of generative AI use

Claude.ai was used to assist with coding and language editing for the multivariate statistical analysis presented in Supplementary Text 2. The author(s) reviewed and edited the output as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2026.105956>.

Data availability

the data is available in supplementary

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